Direct visualization of surface-plasmon bandgaps in the diffuse background of metallic gratings

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When a surface plasmon propagates along a microrough grating, it interacts with the periodic plus the random roughness and emits light into the diffuse background, which can present intensity maxima called diffuse light bands. We reexamine previous studies on these bands within the framework of recent studies on photonic surfaces and show that the phenomenon of diffuse light provides an experimental technique for directly imaging the dispersion relation of surface plasmons, including the gap that, under appropriate circumstances, opens in the reciprocal grating space.

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It is well known that the interface between a vacuum and a metallic surface supports the propagation of surface plasmons (SPs), that is, surface electromagnetic modes that are strongly bound at the interface and propagate with a wave vector $\mathbf{K}_{\mathrm{sp}}$, with

$$\mathrm{Re}\, K_{\mathrm{sp}} = \frac{\omega}{c}\left(\frac{\epsilon}{1+\epsilon}\right)^{1/2} > \frac{\omega}{c}\,, \tag{1}$$

where ϵ is the complex dielectric constant of the metal and ω is the frequency. As $k_0 = \omega/c$ is the wave vector of a free-space photon of the same frequency, SPs are nonradiative modes that cannot be excited by light on a flat surface. One method adopted to overcome the fact that the wave vector needed to excite the SP is greater than that available to incident electromagnetic radiation is to periodically corrugate the surface with a grating structure. When a grating structure is added to the metal, appropriately polarized radiation may then excite SPs when the condition

$$\mathbf{K}_{\mathrm{sp}} = \mathbf{k}_0 \sin\theta_0 + n\mathbf{K}_g\,, \tag{2}$$

where n is an integer, $\mathbf{K}_g$ is the grating vector, $\mathbf{K}_g = 2\pi/d$, and d the period, is satisfied. Assuming that the grating does not perturb the SP (which is the case for shallow gratings), its dispersion relation can be obtained by use of the value corresponding to a flat surface for $\mathbf{K}_{\mathrm{sp}}$. When this is no longer the case, the situation is far more complex because of the formation of bandgaps, and the dispersion relation of a SP propagating along a direction parallel to the Bragg vector $\mathbf{K}_g$, in the form $F(K_{\mathrm{sp}}, \omega, 0) = 0$, may not be found analytically. Therefore numerical modeling is needed to determine the dispersion relation of the SPs and the optical response of the structure. When the SP wave vector has a component parallel to the grooves and ridges of the surface, a situation called conical, by analogy with the conical scattering of light from a grating, a new degree of freedom is introduced, represented by the angle φ that the SP wave vector forms with the Bragg vector. In this case the SP dispersion relation can be represented as

$$F(K_{\mathrm{sp}}, \omega, \varphi) = 0\,. \tag{3}$$

The propagation of SPs in conical situations has been studied by many authors, theoretically as well as experimentally. Mills[1] was the first to study the SP dispersion relation represented by Eq. (3). Other studies investigating the dependence of bandgaps with grating geometry and angle of propagation φ were reported by Seshadri,[2] Watts and Sambles,[3] Barnes *et al.*,[4] Konopsky and Alieva,[5] Kretschmann *et al.*,[6] and Hooper.[7]

Different experimental techniques have been used to obtain maps of the SP dispersion relation by optical means, that is, by studying the resonant interaction between SPs and photons. This is usually achieved by examining the reflectivity,[8] polarization conversion,[3] or optical emission[9] from the grating. Although SPs can couple with light via the grating periodicity, the portion of the dispersion curve that contains the energy gap always lies outside the light lines and so cannot be coupled with photons. Available solutions to this problem include the use of a double-grating technique[3] or a prism coupler.[8]

A technique particularly suited to mapping the dispersion relation of SPs propagating along a grating in the conical case is based on measuring the efficiency of polarization conversion. For example, the experimentally measured reciprocal-space map [that is, the relation given by Eq. (4), below, for a fixed frequency, as a function of propagation direction φ] is displayed in Fig. 7 of Ref. 3 for a gold-coated grating. Note that this map is constructed point by point, since the technique used requires the following steps: (i) measuring the efficiency in the specular order by scanning the angle of incidence θ at fixed φ, (ii) recording the position of the SP resonances, and (iii) repeating the process for different values of φ.

Previous methods for obtaining the dispersion relation of SPs propagating along the grating are based on the fact that the periodicity imposes well-defined directions for the emission of SPs. But real gratings, apart from the periodic roughness, also possess a statistical roughness distributed along the grooves. When the SP propagates along the grating, it interacts with the periodic plus the random roughness and also emits light in other directions different from those of the diffracted orders. Under appropriate conditions, this diffuse background can present intensity maxima called diffuse light bands. Their main experimental features are as follows[10]: (a) The pattern of the bands can be detected at all angles of incidence of the beam. (b) There are some angles of incidence and incident polarizations for which the intensity of the bands is significantly stronger. (c) As the grating is rotated about an axis parallel to the grooves, the position of the bands with respect to the grating does not change. This implies that the bands' relation to the diffracted orders changes with the angle of incidence.

This phenomenon was first reported by Hutley and Bird[10] and has been studied by Cowan,[11] Loewen *et al.*,[12] and Simon and Pagliere.[13,14] A rigorous electromagnetic treatment, simplified with the assumption of one-dimensional statistical roughness, can be seen in Ref. 15. Here we want to draw attention to the following point: the study of the diffuse light bands, generally considered quite a curiosity of noise in the spectrum of a grating, can provide information about the map of the SP reciprocal space, including SP bandgaps. This point seems to have gone unnoticed in previous investigations, probably because they were performed one or two decades before the optics community became interested in the new fields of photonic crystals and photonic surfaces.

Assuming that the mean grating surface is in the $x-z$ plane and that the grooves are along the z direction, a field component of the light that is not scattered into the diffraction orders at the observation point $\mathbf{r} = (x, y, z)$ above the grating ($y > 0$) can be represented with the following plane-wave expansion:

$$f(\mathbf{r}) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} A(\alpha, \gamma)\exp[i(\alpha x + \beta y + \gamma z)]\mathrm{d}\alpha\mathrm{d}\gamma\,, \quad (4)$$

where $A(\alpha, \gamma)$ is the complex amplitude and $\alpha^2 + \beta^2 + \gamma^2 = \omega^2/c^2$. For waves propagating along a direction characterized by spherical angles θ and φ,

$$\alpha = \frac{\omega}{c}\sin\theta\cos\varphi\,,$$

$$\beta = \frac{\omega}{c}\cos\theta\,,$$

$$\gamma = \frac{\omega}{c}\sin\theta\sin\varphi\,. \quad (5)$$

We can obtain the angles θ and φ associated with the diffuse light bands by phase matching these waves to a SP propagating along the grating. By doing so, we obtain the following conditions that relate the angular position of the bands with the components of the SP wave vector $\mathbf{K}_{\mathrm{sp}}$:

$$\frac{\omega}{c}\sin\theta\cos\varphi = K_{\mathrm{sp}}\cos\varphi + n\frac{2\pi}{d} = \mathbf{K}_{\mathrm{sp}}\cdot\hat{x} + n\frac{2\pi}{d}\,,$$

$$\frac{\omega}{c}\sin\theta\sin\varphi = K_{\mathrm{sp}}\sin\varphi = \mathbf{K}_{\mathrm{sp}}\cdot\hat{z}\,. \quad (6)$$

In Refs. 12–14 the geometrical form of the bands and their angular position near the line of the orders were predicted fairly well by use of Eqs. (6) and by assuming that the wave vector $\mathbf{K}_{\mathrm{sp}}$ of the SP has a value corresponding to that of a flat metallic surface. However, Eqs. (5) show that we can obtain the reciprocal-map space $(\mathbf{K}_{\mathrm{sp}}\cdot\hat{x}, \mathbf{K}_{\mathrm{sp}}\cdot\hat{z})$ by recording the angular position (θ, φ) of the bands. Therefore the situation is completely similar to gaining access to the reciprocal space by recording the position of SP resonances in reflectivity minima but with an important practical difference: recording the position of the bands makes the angular scanning, in this case provided by the random roughness, unnecessary.

Since it is clear that the position of the bands provides a map of the SP reciprocal space, the diffuse light bands produced by gratings such as those reported in Ref. 3 should exhibit the presence of a photonic gap in the SP dispersion equation. To the best of our knowledge this possibility has never been reported, even when it was likely that the manifestation of the gap was present in previous studies of diffuse light bands.

To investigate this possibility we recorded the diffuse background produced by a commercial ruled grating (Edmund Scientific, Barrington, N.J.) that was aluminum coated, with a frequency of 1200 lines/mm and a blaze angle of 8°. A characterization of the grating was made by use of an atomic-force microscope Nanoscope III Multimode-AFM (Digital Instruments, Veeco Metrology, Santa Barbara, Calif.) with a J-type piezoelectric scanner working in tapping mode. The grating profile is shown in Fig. 1. The measured height and period are 73 and 810 nm, respectively. In Fig. 2 we show the experimental setup used to obtain

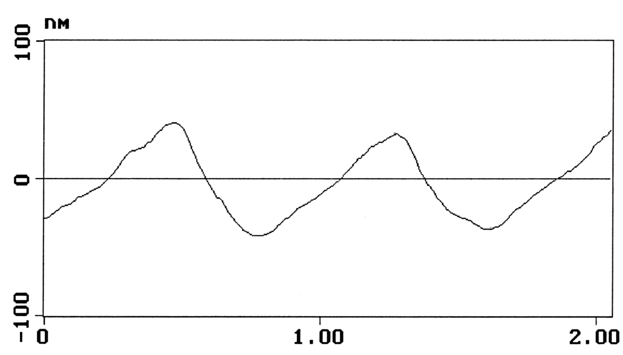

Fig. 1. Grating profile obtained from atomic-force microscope image.

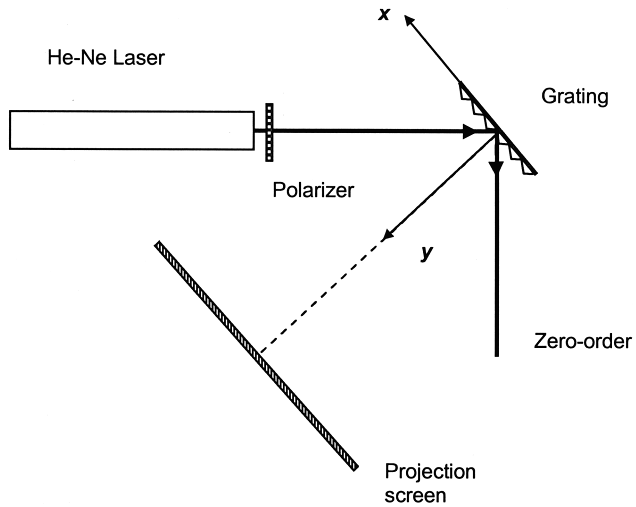

Fig. 2. Experimental setup to observe the bands.

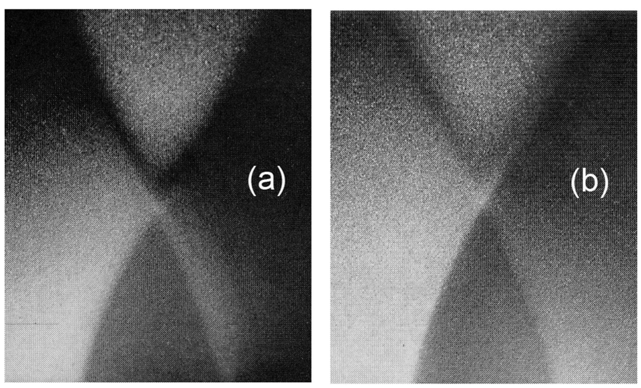

Fig. 3. Portions of the bands for (a) p-polarized and (b) s-polarized incidence.

the image of the bands. A He–Ne laser impinges on the grating, and the dispersed light is projected onto a screen and registered by a camera. Figure 3 shows the same portion of the system of diffuse bands observed under different conditions of illumination: in Fig. 3(a) the laser is p polarized, whereas in Fig. 3(b) it is s polarized. In both, the total scattered light was recorded. The similarity between the shapes of the diffuse bands shown in Figs. 3(a) and 3(b) and the reciprocal-map space obtained by other methods, as shown, for example, in Fig. 7 of Ref. 3, is evident. The similarity includes the bandgap.

To estimate the SP bandgap one must take into account the geometry of the screen on which the diffuse bands are projected. For example, if a plane screen is located at a distance R_0 and parallel to the mean grating surface, the projected bands are described by position vector $\mathbf{r}_b$

$$\mathbf{r}_b = \frac{c}{\omega} R_0 \left(\frac{\mathbf{K}_{\rm sp} \cdot \hat{x} + n \dfrac{2\pi}{d}}{\cos\theta} \hat{x} + \hat{y} + \frac{\mathbf{K}_{\rm sp} \cdot \hat{z}}{\cos\theta} \hat{z} \right). \quad (7)$$

To estimate the gap we directly measured the minimum distance Δz between dark edges, the coordinates of these edges on the projection screen, and the distance R_0 between the screen and the grating. From this information the width of the bandgap ΔK_z in the reciprocal space can be obtained from Eq. (7). In our case we obtained $\Delta K_z \approx (0.09 \pm 0.01)(\omega/c)$. In passing, we note that this value is of the same order of magnitude as the one that can be inferred from Fig. 7 of Ref. 3 for a gold grating with a quite similar profile.

To conclude, the results of this Letter show that diffuse light bands, usually considered a curiosity of noise in the spectrum of a grating, can provide an experimental technique for directly imaging the dispersion relation of SPs, including the gap that, under appropriate circumstances, opens in the reciprocal grating space.

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